the

meteorological magazine

551.509.335:551.589:681.31/.34

WORK IN SYNOPTIC CLIMATOLOGY WITH A DIGITIZED DATA BANK

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Summary. An account is given of a bank of digitized data containing over 100 million decimal digits which is used by the Synoptic Climatology Branch of the Meteorological Office. The pr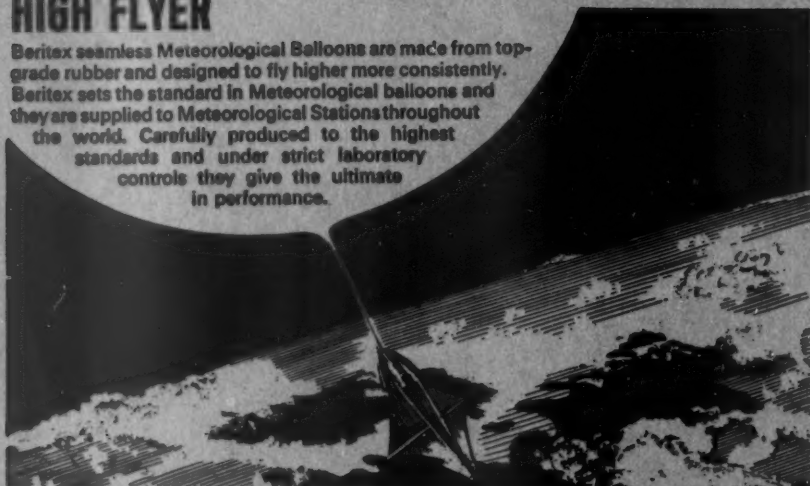oblems involved in bringing the bank into usable condition are illustrated, and a bibliography is given of papers on long-range weather forecasting and related subjects which have used data drawn from the bank.

The following are the main headings used in the paper: Introduction; The main constituents of the long-range data bank; Routine and research processing; Operational forecasting requirements; Applications of the long-range data bank; Examples of computation; A case history of important data; Quality control and the correction of errors; Comments and conclusions; Bibliography.

Introduction. For the past 100 years most meteorological work has fallen under one of two headings, namely synoptic meteorology (which analyses space fields of contemporaneous data by non-statistical methods with the object of short-range forecasting) and climatology (which uses long records of data from single stations which are analysed statistically and often in isolation). The two aspects have to be considered together in synoptic climatology, a newer study of which the work on long-range forecasting described below forms a part. In the British Meteorological Office, in which a centralized computer installation provides a service to all branches, the power of the central processing unit is determined by the very exacting requirements of short-range numerical weather forecasting, so that the users with mainly statistical interests have access to a computer far more powerful than they could ever justify for themselves. Their problem lies with the supply of data in usable form, and in deciding what to instruct the computer to do with them. Given reasonable organization, the computer time spent on carrying out the instructions is not the prime consideration. Any investigator concerned with long-range weather forecasting and allied projects faces an enormous task in the collection and reduction of data, and from the time we, in the Synoptic Climatology Branch, first attacked the problem in 1953 we concentrated on fields narrow enough to enable visible progress to be maintained. By 1965, when with the new KDF 9 computer we first had facilities

for using magnetic tape, we already had a considerable digitized library punched on paper tape, and also the practical knowledge described by Craddock (1966 *(a)*), of working with the far less sophisticated Mercury computer. We decided that as no suitable macrolanguage was on offer we should develop our own, the result being the original METO language described by Craddock (1966 *(b)*).

Apart from fewer than 20 computations, all the work to be described was carried out using a main-store claim not exceeding 48K bytes,* and without ever claiming more than two magnetic tapes at once. Thus almost everything could have been done on a computer very much smaller than that actually used. The effort spent in language design and implementation produced useful returns soon after the installation of the KDF 9 computer, and materially helped in the assembly of the data bank described below.

Long-range weather forecasting differs from short-range forecasting in that the individual situation may last weeks or months and can readily be obscured by short-period fluctuations. Whereas an experienced short-range forecaster can rely on his memory for enough relevant past situations to guide him, a long-range forecaster cannot do so, and must have access to an external memory of relevant data covering as long a period as possible. The build-up of this memory started in 1953, using as media charts, diagrams and edge-punched cards, and has continued ever since. From 1965 onwards both new and existing data have gradually been transferred to magnetic tape. The subject calls for data of two kinds, *(a)* for use as predictors: data covering large areas in space and long periods in time, which between them determine the character of atmospheric processes on the largest scale, and *(b)* for use in determining possible predictands, etc.: very long series of daily measurements of elements for a network of stations covering the British Isles. The data of the first type, which are of interest to all long-range forecasters, can relate to little more than the last 100 years, since before then there is a lack of information from the remote areas which include many of the main centres of atmospheric action. The data of the second type may extend back further, but of course the data on predictands in the British Isles are of less interest in other countries, although they are also used for climatological purposes in Britain. Even with computer facilities the collection of data from many countries and periods, and the reduction of a variety of units, formats and conventions to common standards, is a formidable task, and one which precedes and continues alongside the use of the digitized data bank for productive work.

The main constituents of the long-range data bank. In the following list only the constituents comprising non-trivial numbers of data have been included. Items such as the annual sunspot numbers are too few to involve data-processing problems, though they are often considered in research and operations.

(i) *Hemispheric fields of the 500-mb surface.* These represent the mean airflow of the troposphere. Each daily field is represented by the values at the points of the German Upper Air Grid, which uses 592 numbers per chart.

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* K = 2^{10}; 1 byte = 8 bits; 1 bit is a binary digit.

The daily data for years 1949 to 1964 were obtained from copies of cards punched by the Deutscher Wetterdienst from charts analysed in Germany. Data for 1965 to the present have been taken from charts analysed by the Meteorological Office. For the years 1951 to 1964 deficiencies over the Pacific Ocean have been remedied to some extent by 5-day mean data received on magnetic tape from the Japanese Meteorological Agency, based on charts analysed in the United States of America or in Japan.

The 7300 daily charts contain about 4·3 million numbers, or *17 million decimal digits.*

(ii) *Hemispheric fields of the thickness of the 1000–500-mb layer.* These fields, which represent the mean temperature of the troposphere, are similar to the preceding item, and were obtained in the same way. They too comprise *17 million decimal digits.*

(iii) *Hemispheric fields of the 1000-mb surface.* These fields, which represent the algebraic differences of the first two, approximate to fields of the MSL pressure. They comprise *17 million decimal digits* but, of course, they only cover the years since 1949, whereas analysis of the MSL pressure existed long before then, and are represented in (iv).

(iv) *Grid values for the MSL pressure over the northern hemisphere.* Daily values for the years since 1899 were obtained from the United States Weather Bureau (Washington) on magnetic tapes from cards punched from the historical weather maps. *Total 45 million digits.*

To these have been added daily values for the same grid for the period December 1880 to February 1900. These values cover a more limited area excluding most of the Pacific Ocean, and are taken from the German/Danish charts for the period. They were provided on magnetic tape by the Deutscher Wetterdienst. *Total 10 million digits.*

(v) *Monthly mean values of MSL pressure.* For years from 1899 onwards, data at the points of the German Upper Air Grid were extracted from German charts and punched by the Synoptic Climatology Branch. Similar data for years 1873–98 were assembled from whatever sources exist. *Total 0·5 million digits.*

(vi) *Descriptions of the large-scale weather situation near the British Isles.*

   (a) Lamb's daily weather catalogue 1861 to 1968 (to be published),
                                                                                          79 000 digits
   (b) Ward's catalogue of daily weather 1873 to 1968   **70 000 digits**
   (c) PSCM indices (described by Murray and Lewis (1966))
                                                                                          79 000 digits
   (d) Grosswetterlagen daily weather catalogue (1880–1968)
        (Hess and Brezowsky (1969))   **130 000 digits**
                                                                                  Total 358 000 digits.

(vii) *Monthly data taken from the Smithsonian World Weather Records etc.* These are mostly monthly mean temperatures for about 350 stations, and monthly rainfall totals for 100 stations forming a network over the northern hemisphere. Many of the records extend back to 1850 or earlier. *Total 3·75 million digits.*

(viii)   *Fields of the sea surface temperature anomaly over the North Atlantic.* These fields, which seem to provide one of the most useful diagnostics of the character of the future weather in the British Isles, are derived from many millions of Hollerith cards prepared by various services (and exchanged internationally) for use in marine climatology. The data are now being averaged in forms suitable for use in long-range weather forecasting. *Total 7 million digits.*

(ix)   *Bathythermograph data.* These data give the three-dimensional thermal structure in the oceans. Data on magnetic tape now include most of nine ocean weather stations A, B, C, D, E, I, J, K and M for most days since 1 January 1966. *Total 5 million digits.*

(x)   *Data for determining predictands.* These include daily values of three elements — maximum and minimum temperatures and rainfall — for Kew (1881–1968), Bidston (1870–1968), Oxford (1853–1968), Plymouth (1864–1968), Armagh (1867–1968), Edinburgh (1895–1968) and Glasgow (1878–1968). *Total 2 million digits.*

The total number of data in the long-range bank is well over 130 million digits, stored on over 120 magnetic tapes. This is perhaps one hundredth of the total stock of digitized data held by the Meteorological Office, but unlike the main stock, which is held as an archival store to serve all purposes, the long-range bank contains only material selected for relevance to a particular field of study.

Routine and research processing. The data already collected include a large fraction (probably over half) of all the independent measurements which have ever been made and which are relevant to the problem of long-range weather forecasting for the British Isles. A forecaster concerned with future conditions in, say, Hungary or Japan would require further data not relevant to the British Isles and, of course, different selections of data could be made which would have represented the same facts; but the general effect is that the task of data assembly, which has frustrated every investigator into the long-range problem, is becoming less pressing, while attention is shifting to the problem of making better use of the data we have. Doing this is less straightforward than it appears to be, because of the very variable quality of the data. The acquisition of digitized data is only the first step towards using them, and considerable effort and delay is involved in the operations of reducing data to common standards, and eliminating at any rate the larger errors which are described on pages 228 and 229. One of the conclusions of this paper is that these operations of error detection and correction are a function of the research unit using the data, which alone knows the tolerances which can be accepted in the work in hand. In practice a data bank of 10^8 digits cannot be checked and corrected in a few days, so the most important data were treated first and have since been used for productive work while operations of quality control are carried out on other parts of the data bank. The mere effort of punching 10^8 decimal digits represents a substantial investment of man-hours and, wherever possible, data have been acquired by exchange, purchase or extraction of material which has already been converted to digitized form by others, for example, for use in synoptic meteorology or for climatology. Direct punching of data by the staff of the unit concerned with long-range weather forecasting has been kept to a minimum for filling gaps in important records, for making corrections, and for computer programmes.

Operational forecasting requirements. In statistical terms, the data relating to a large-scale weather situation are the predictors in a vast multi-variate problem, in which a combination of meteorological insight and statistical reasoning is used firstly to put the predictors into some kind of order of merit, and secondly to discern what is or is not a reasonable target for prediction. The monthly forecasts issued by the Meteorological Office, besides their other functions, serve as a test bed on which new tools can be developed and brought into use, such as the *PSCM* indices described by Murray and Lewis (1966), the applications of eigenanalysis outlined by Craddock and Flood (1969) and the uses of sea surface temperature anomalies described by Ratcliffe and Murray (1970). With only one forecast every fortnight, the evidence for the success or otherwise of any proposed technique grows only slowly, but over 150 official monthly forecasts have now been made, and the rising standards of these have been described by Ratcliffe (1970). This evidence is supported by that of experimental long-range forecasts for other periods, and suggests that gradual progress is being made towards understanding the slower large-scale atmospheric changes.

Applications of the long-range data bank. The long-range data bank is kept in a state of constant activity, partly for operational work, which includes routine steps for updating and for the detection and correction of errors, and partly for research work. Its availability has enabled the Synoptic Climatology Branch to achieve a high level of scientific productivity, as instanced by the publication in the years from 1966 onwards of between 50 and 100 scientific papers and reports. The level of computer activity averages at about 70 computations per week, programmed by one of from 5 to 10 people, involving on average between 90 and 100 claims for magnetic-tape mounting. The monthly consumption of computer time for research is about 30 hours, one tenth of the total non-priority work of the Meteorological Office, while operational long-range work is included with the other priority work which makes up the bulk of the 140- to 150-hour week of the KDF 9 computer. Thus the average user programmer initiates two computations per day, each of which runs for less than six minutes and uses one or two magnetic tapes. However, the part played by the computer is definitely that of a help to, and not a substitute for, the human intelligence. The computer can carry out routine operations far more quickly and accurately than can be done by hand, but the decisions are taken by scientists who can apply judgement to a range of issues wider than those with which the computer is programmed to deal. Only when experience shows that a decision is in fact always made according to definite rules is the computer programmed to make the decision. Thus the computer plays an important and increasing but essentially subordinate role in operational long-range weather forecasting. Among its main tasks are :

(i)   the production and printing of time-averaged fields, e.g. mid-month to mid-month surface pressure charts for all 30-day periods from 1880 up to date, from daily data,

(ii) computerized pattern matching, with results displayed in order of merit,

(iii) eigenvector analyses used for matching 500-mb charts, and for error detection,

   (iv)   producing standard statistics for description and error detection, and

   (v)   the calculation and statistical description of proved or experimental derived data, such as normals and eigenvector coefficients.

Examples of computation. The following are examples of different applications.

(i)   Computed average fields are printed out by means of the 'zebra chart print facility' in which the chart appears in clear and printed stripes, and the contours are drawn by running a pencil or pen along the edge of the stripes. This output may be less elegant than that of the computerized line-drawer, but it is very much quicker and simpler, and the final stages of chart analysis make a break in the monotony of handling endless arrays of figures.

(ii)   As an example of a routine computation carried out fortnightly, we may take the selections of analogues by means of Lamb's weather catalogue. The stages are as follows :

   (a)   The series of daily weather types for the past 30 days is matched against those for the same dates in a preceding year, the measure of similarity being judged by a carefully designed scoring table.

   (b)   The comparison is repeated, using a shift backwards or forwards of up to 14 days, and the best of the 29 values taken to represent the year.

   (c)   Stages *(a)* and *(b)* are repeated for all past years from 1873 to 1968.

   (d)   The year scores are considered, their mean and standard deviation are found, and all scores are normalized in units of the standard deviation.

   (e)   The years are ranked in order of merit, and for all years the year numbers, scores and shifts are placed ready to print.

   (f)   Stages *(a)* to *(e)* are repeated three times more using scoring tables designed to measure the northerliness, the blocked character or the cyclonicity.

   (g)   The results are printed out in tables, ready for consideration, with other evidence, by a panel of forecasters.

(iii)   A major research calculation, using some of the 500-mb data, has been described by Craddock and Flood (1969); this forms the basis of much work now in progress. One of the essential steps, carried out in three operations, consisted in the extraction of 130 wanted items from each of over 6000 arrays of 592, the detection and estimation of missing values, and their conversion into a covariance matrix of order 130. This was one of the few (less than 20) operations carried out by the Synoptic Climatology Branch which required a full claim (of 120K bytes) of the core store of the KDF 9 computer. Following this work, the daily values of the 50 next important eigenvectors have been found for every day since 1 January 1949, and have then been sorted into yearly blocks, stored, and used to produce routine statistics. Completion of the work must be delayed pending the elucidation of some impossible values in the earlier years, as mentioned on pages 222 (i) and 228.

(iv) The importance of these 500-mb data makes it desirable to obtain estimates of the same fields for years before 1949, and the efforts to do this described below have proved surprisingly successful.

Comparisons of the fields of the monthly mean anomaly of MSL pressure with the anomalies of 1000–500-mb thickness show that a substantial negative pressure anomaly is usually accompanied by a negative thickness anomaly some 10 degrees further west, and somewhat further north. The data for the recent years for which both measurements are available have been used by Ratcliffe and Collison to produce regression equations which enable the thickness anomaly patterns to be estimated from the MSL pressure anomaly patterns for earlier years. Adding the observed MSL pressure anomaly fields to the estimated thickness anomaly fields gives an estimated 500-mb anomaly field. These fields when used as the basis for selecting analogues of the 500-mb field produce results which appear to have predicitive value.

These examples of the application of the digitized data bank could be multiplied almost indefinitely; the fact is that it has enabled the Synoptic Climatology Branch to reach a state of something near full productivity, but attention must now be given to the important if uninspiring problem of the reduction of data to common standards, and the elimination of errors. This is illustrated by the case history which follows.

A case history of important data. The fields of 500-mb height, mentioned on page 222 (i) and in (iv) above, provide what is probably the most important single diagnostic of the current state of the atmosphere, and the fields of the 1000–500-mb thickness which represent the mean thermal distribution in the greater part of the troposphere are almost equally important.

Charts of these elements have been produced daily since the 1940s, and from 1 January 1949 the values for the points of the German Upper Air Grid were punched on Hollerith cards, 36 cards per chart. Copies of these cards for each day of the years 1949 to 1964 were received by the Meteorological Office from the Deutscher Wetterdienst in exchange for other data, and were transferred to magnetic tape (in blocks of 592 numbers per chart). From 1965 to date, the values from similar charts produced in the British Central Forecasting Office have been read by the Synoptic Climatology Branch at the points of the German Upper Air Grid, punched on paper tape, and transferred to magnetic tape, so that a homogeneous series of fields is stored from 1 January 1949 up to date.

These data, which are stored on four magnetic tapes and regularly updated, are in constant use for the production of time-mean charts for forecasting purposes. A series of the printed versions of the daily charts is kept, but the time-mean charts are discarded after use. These data were checked thoroughly before use, in the way described in the next paragraph, and formed the basis for the large-scale eigenvector analysis described by Craddock and Flood (1969). Once the eigenvectors had been found, daily values of the coefficients of the 50 most important were calculated, sorted into yearly blocks and stored permanently. The calculation of descriptive statistics for these coefficients and the investigation of their interrelationships is still in progress. The scope of this work was limited by shortage of data over the Pacific Ocean, and this deficiency has been reduced by means of data received on magnetic tape

from the Japanese Meteorological Agency. These data, before being usable, had to be converted in a manner similar to that used on the German data, but with a complete rearrangement in addition.

Quality control and the correction of errors. The importance of quality control, or the detection of errors and missing or incredible values in data, increases with the size of the data bank. A scientist working on 1000 data has some excuse for thinking that by taking enough care he can ensure that his data are entirely free from error; he can if he wishes, give individual attention to every digit. His colleague with a data bank of 100 million digits (about the number of letters used in the *Encyclopædia Britannica*) can never give his attention to more than a tiny fraction of the total and must realize that some errors may have escaped all previous attempts to eliminate them. For example, the punched cards bearing the 500-mb data discussed in the last paragraph were certainly checked before they left Germany, but the data were tested again after transfer to magnetic tape by comparing every value with the mean and standard deviation for its position and time of year. This check revealed about 40 discrepancies which could be ascribed with some confidence to punching errors. These were corrected, but the analysis of Craddock and Flood (1969) showed that one of the 250 000 punched cards must have been lost at some stage. Later the calculation of eigenvector coefficients produced impossible values for a few fields in the years 1949, 1950 and 1957, so that there is still something to be explained. More recently, Colgate has developed a new and very effective method of error control, in which the field as originally punched is compared with a similar field reconstituted from the coefficients of the 40 most important eigenvectors. This method serves to detect errors which would have escaped previous checking procedures, and is being applied as a routine to all new 500-mb fields as they are added to the data bank. The task of applying it to past data remains for the future.

The question of error control has always been important to synoptic meteorologists who receive their data by telecommunication. There is enough redundant information in most weather messages to allow most of the important errors to be picked out if the data are plotted on a chart, but this protection loses its value if the data are digitized for storage in a way which, although it does not preclude spatial comparisons, makes it difficult for the future investigator to carry them out. The recommendation of the World Meteorological Organization, expressed in *World Weather Watch Planning Report* No. 28 (1969) is that effective quality control of all data should take place when data first enter the world's meteorological archives, but the attainable standards have yet to be determined, and in any case, they can only apply to new accessions to the world's data banks, and not to data which have been digitized in the past. The quality control of meteorological data has been discussed by, among others, Sumner (1969) and Filippov (1968) who quotes the experience of several of the world's main centres for meteorological telecommunications. Their evidence suggests that when land data are punched by professional meteorological staff, one wrong digit is punched on average in every 1000 to 2000. Thus it would appear, if all errors were equally likely, that a system of double punching with comparison should reduce the error rate to one in from 10 million to 40 million. Unfortunately, all errors

are not equally likely; for example, an error in which two figures are reversed or in which, say 557 is punched for 577, has far more than the average probability of occurrence. Moreover, figures which are badly made, or smudged in the original document may be misread twice.

Computerized quality control is possible by comparing data against statistical standards such as means and standard deviations, by internal checks between related data in the same observation, by spatial or temporal comparisons between observations, or by the more sophisticated eigenvector technique mentioned on page 228. All methods take time, and all share the feature that the most the computer can do is to indicate a certain value as being probably or certainly wrong, and perhaps to suggest a reasonable replacement value. Moreover, while the computer can be programmed to treat certain values as acceptable, and others as quite incredible, there is bound to be a penumbra of values, including the genuine extremes of the measurement in question, which lie outside the usual limits but may never-theless be accepted in view of supporting evidence from other sources. In these cases at any rate the question whether to accept the suspected value must be a matter for human judgement, so that the computer must be programmed to retain values which are suspect but not incredible until judgement can be passed on them. Thus while error detection, or the identification of doubtful values, can be computerized to a large extent, error correction remains largely a matter for man, and therefore one which progresses at the working pace of the human mind.

Besides the more obvious types of error, such as punching errors, which occur often enough to be recognized and provided for in computerized schemes of error detection, a very large digitized data bank is liable to contain examples of extremely improbable errors which at first sight should never occur, and against which protection could be secured only at extravagant cost. The work of Badger and Lyness (1969), which describes some meteorological statistics prepared for the gas industry, gives three examples of such errors. In one the data for a whole year were wrongly ascribed to another, in the second the punching instructions had been misunderstood when part of a long record was punched, and in the third a number of data were presented in the wrong order. In each case the mistake, unless detected almost at once, is liable to escape notice until an analysis is carried out which produces peculiar results casting suspicion on these data. Because of the risk of individually improbable errors, it is worthwhile, when planning an investiga-tion based on a large data bank, to produce results in parallel from sections of the data. Results which confirm one another by falling into a reasonable statistical distribution may be pooled to produce results based on the whole evidence, whereas anomalous results can be recognized and given individual attention.

Comments and conclusions. Our conclusion is that the scientist who relies on a digitized data bank for raw material must learn to live with data which are not error free. He must devote some effort to trying to ensure that his data are up to standard, and must plan his work on robust lines, so that a few undetected errors do not lead to catastrophe. His method of computer control, be it macrolanguage or package of subroutines, must be able to cope with problems of the extraction, correction and manipulation

of data as well as with those of the intended field of study and must be capable
of switching from one type of operation to another with fluency and dexterity.
The METO language described by Craddock (1966 *(b)*) and Craddock
and Freeman (1967) is one example of the type of tool required for building
up and using a digitized data bank on the scale described, and the best evidence
of its efficiency is the bibliography which follows.

Bibliography. This bibliography combines the references made in this
paper with a convenient record of the main publications of the Meteorological
Office on long-range weather forecasting since 1966. Nearly all the items
involve the use of the long-range digitized data bank or the METO computer
language, or both.

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PSCM INDICES IN SYNOPTIC CLIMATOLOGY AND LONG-RANGE FORECASTING

By R. MURRAY and P. R. BENWELL

Summary. The *PSCM* indices of Murray and Lewis have been recomputed from a revised and extended Lamb catalogue of daily synoptic types near the British Isles. Long-term and seasonal variations of synoptic types and the correlations of the indices with rainfall and temperature are discussed. Examples of the usefulness of the indices in specifying large-scale circulation anomalies and in weather forecasting on the monthly and seasonal time-scales are presented.

Introduction. The *PSCM* indices, which were introduced by Murray and Lewis,[1] are intended to measure in a succinct and meaningful way the main characteristics of the synoptic situation over long periods from the daily weather types over the British Isles in the catalogue prepared by Lamb.[2]

Since the original work on these indices was carried out, Lamb[3] has reclassified the daily synoptic maps and extended his catalogue back to 1861. This re-classification was desirable in order to homogenize the series since most of the earlier catalogue did not include the south-east, north-east or south-west directional types. The definitions of, and the detailed procedure for obtaining, the indices have not been changed and they are given in the earlier paper.[1] Here it need only be mentioned that the *P* index is a measure of the difference in frequency of days of progressive and days of blocked synoptic types — *P* is positive when the bias is towards progressive synoptic types. The *S* index aims to measure the difference in frequency of southerly and of northerly days over or near the British Isles — *S* is positive when the bias is southerly. The *M* index measures the frequency of days with meridional (i.e. northerly or southerly) synoptic types over the British Isles. The *C* index gives in effect the difference between frequency of cyclonic and of anticyclonic days over the British Isles — *C* is positive when cyclonic days predominate. The ranges over which the indices occur are readily seen in the Appendices. In the present article recomputed values of various quantities and some new synoptic-climatological material related to the indices are presented.

Seasonal and long-term variations.

(i) *Index of progression, P.* The long-period mean values of the *P* index in Figure 1 confirm the marked seasonal variation in progressiveness near the British Isles. Progressive synoptic types predominate in winter (maximum
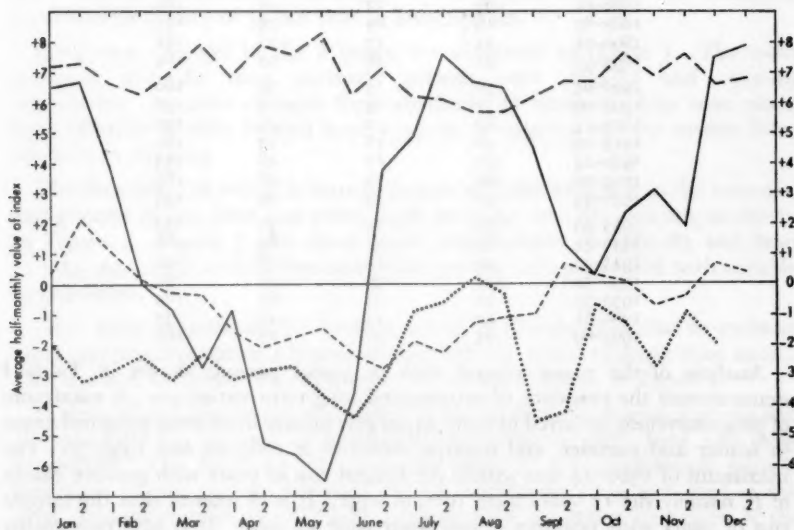

FIGURE 1—AVERAGES OF HALF-MONTHLY VALUES OF *P, S, C* AND *M* INDICES
FOR THE 100-YEAR PERIOD 1865–1964

On the abscissa the period 1st to 15th of each month is indicated by 1 and the remainder of the month by 2.

———— *P*   – – – – *S*   .... *C*   — — — *M*

in the second half of December — called, for convenience, late December) and in summer (maximum in late July). Non-progressive or blocking synoptic types are evidently at a maximum in late May with relative maxima of blocking in late March and early October. Examination of the frequencies of half-month periods with $P \geqslant 0$ and with $P < 0$ show only slight changes in the pattern suggested by Figure 1. The winter maximum frequency of $P \geqslant 0$ is actually 72 per cent in early December but the frequency is near 70 per cent from late December to late January; the summer maximum occurs in early July (71 per cent) but the frequency is generally near 70 per cent throughout July and August. The maximum frequency of blocking $(P < 0)$ is in early May (67 per cent) but the frequency is only slightly less in late April and late May; relative maxima of blocking occur in late March (58 per cent) and early October (52 per cent) as suggested also by Figure 1.

It is noteworthy that there is a sudden increase in progressiveness from early to late June, shown in Figure 1, related to the development of the so-called European monsoon. Other noteworthy changes in progressiveness are the decrease from early to late February and the increase from late November to early December.

TABLE I—MEAN ANNUAL VALUES OF P, S, C AND M INDICES IN 5-YEAR PERIODS FROM 1865 TO 1969

Period	P	S	C	M
1865–69	76	− 35	− 78	160
1870–74	50	− 16	− 42	168
1875–79	10	− 21	− 15	173
1880–84	68	22	− 53	185
1885–89	− 19	− 29	− 73	171
1890–94	34	− 17	− 77	181
1895–99	21	− 18	− 97	164
1900–04	56	3	− 55	180
1905–09	73	− 24	− 74	156
1910–14	47	2	− 44	159
1915–19	40	− 48	− 43	164
1920–24	149	10	− 28	154
1925–29	86	− 13	− 36	165
1930–34	47	− 14	− 55	155
1935–39	35	− 19	− 46	153
1940–44	65	− 31	− 84	162
1945–49	40	14	− 78	144
1950–54	117	− 39	− 35	161
1955–59	− 23	− 24	− 89	184
1960–64	22	− 15	− 43	173
1965–69	− 24	− 37	− 25	168

Analysis of the mean annual data in 5-year periods shown in Table I demonstrates the existence of pronounced long-term variations. A maximum of progressiveness occurred in 1920–24, largely arising from great progressiveness in winter and summer, and minima occurred in 1965–69 and 1955–59. The maximum of 1920–24 was within the longest run of years with positive values of P, namely the 17 years from 1916 to 1932. It is of interest that the longest run of years with negative P was from 1958 to 1960. It is also noteworthy that a very large change in the mean values of P took place from 1950–54 to 1955–59. Ratcliffe and Murray[4] have shown that progressive synoptic types near the British Isles are associated with higher than usual sea temperatures near Newfoundland and that the blocked types are associated with the lower than usual sea temperatures. It is of interest to note that almost all

months in 1950–54 had higher than usual sea temperatures near Newfoundland, whereas in 1955–59 the sea was generally colder than usual. In the recent past a remarkable change in progressiveness occurred from 1967 ($P = 117$) to 1968 ($P = -99$). These examples should be a warning that large changes from year to year or from one group of years to the next could well happen again.

The seasonal changes (averaged over 100 years) shown in Figure 1 are of course not exactly reproduced every 5-year period. Nevertheless, the half-month maximum of progressiveness over the year occurred in July/August or December/January in most cases, the main exceptions being early March 1875–79 (mean $P = 14$) and early May 1960–64 (mean $P = 13$). Moreover, the yearly maximum of blocking (minimum in P index) every 5-year period was generally a feature sometime between late February and early June, but the yearly maximum occurred in late September in 1905–09 and in early October in 1865–69 and 1910–14.

(ii) *Indices of meridionality, S and M.* The seasonal variations of the S index (southerly bias being positive) are shown in Figure 1. The bias to northerliness in spring and summer and also in late autumn and to southerliness from late September to late October and in winter (especially late January) is quite obvious. Examination of the half-monthly values shows that the maximum frequency of negative S (northerly bias) reaches 65 per cent in late July rather than in late June as suggested by Figure 1, but relative maxima of 63 and 61 per cent occur in late June and late April respectively, in agreement with the indications from Figure 1. Moreover, northerly bias reaches a minimum frequency of 35 per cent in late January.

Long-term changes in the S index are suggested by Table I. The most southerly and the most northerly periods were 1880–84 and 1915–19 respectively. Notable changes from southerly to northerly bias took place from 1880–84 to 1885–89 and from 1945–49 to 1950–54 and the reverse from 1915–19 to 1920–24.

Meridionality (M index) is least in August and generally low in the summer, and greatest in late May and rather high in spring and late autumn, as shown in Figure 1. Figure 1 also shows most meridionality in 1880–84 and least in 1945–49, and it is of interest that both periods were associated with notable southerliness.

(iii) *Index of cyclonicity, C.* Positive values of C indicate a bias to cyclonic types and negative values a bias to anticyclonic (or to less cyclonic than usual). The seasonal variation (averaged over 100 years) is shown in Figure 1.

A well-defined maximum of cyclonicity occurs in early August and minima of cyclonicity (or maxima of anticyclonicity) occur in early June and early September. The frequency of occurrence of $C \geqslant 0$ in half-month periods falls from 56 per cent in the early August maximum to 33 per cent in the early September minimum. There appears to be a relative minimum of the C index in early November which was not in evidence in the monthly data presented by Murray and Lewis.[1]

The changes in the annual mean values of the C index over the long period are shown in Table I. The most cyclonic period was 1875–79 and the most anticyclonic period was 1895–99.

Quintiles and extremes. Quintile boundaries were computed for the 100 years from 1869 to 1968 for various periods from a half-month to a season. Monthly and seasonal data are presented in Appendix I and some extreme values of the indices in Appendix II. These will not be discussed here.

Association between the indices and rainfall. In the earlier paper[1] the association between C and R (average monthly rainfall over England and Wales) was demonstrated by means of contingency tables. It was pointed out that the correlation was generally good between C and R each month but much weaker between P and R and between S and R. Subsequently, from district data for the period 1926 to 1966, Perry[5,6] showed the spatial variation of the relationships over the British Isles. The revised data have been correlated against monthly rainfall over England and Wales (R) and against monthly rainfall over Scotland (R_s).

For England and Wales C has a highly significant correlation with R for every month — the correlation coefficient ranging from 0·87 in July to 0·77 in May. P and R are significantly correlated at the 5 per cent level only in February (0·39), September (0·24) and November (0·28), but their correlations are much lower than those for C and R. Significant correlations obtain between S and R in January (0·25), June (0·39) and December (0·26). M and R are not significantly correlated in any month. Multiple correlation coefficients between R and P, S and C were computed for each month, but these do not differ significantly from the simple correlation coefficients between R and C.

Similar correlations were computed between Scottish rainfall (R_s) and the indices. C and R_s are very significantly correlated each month — the correlation coefficient ranging from 0·75 in September to 0·50 in March. These are all lower than the corresponding correlation coefficients between C and R. However, R_s and P are also very significantly correlated each month (the correlation coefficients vary from 0·72 in February to 0·35 in July). Thus there is a much better correlation between P and R_s than between P and R at all seasons. The biggest difference between the correlation coefficients applies in March when $r(P, R) = 0·08$ and $r(P, R_s) = 0·68$, but there are quite large differences in all the other months. It is synoptically reasonable that rainfall over Scotland is much more closely related to the progressiveness of the synoptic types over the British Isles than is rainfall over England and Wales. There are three significant correlations between S and R_s, namely in June (0·38), July (0·29) and December (0·25) — these are about the same size as the correlation coefficients between S and R. Unlike the M and R case, the correlations between M and R_s are significant at the 5 per cent level in four months, namely January (– 0·28), February (– 0·21), March (– 0·28) and November (– 0·26). The correlation coefficients between M and R_s in these and in the other eight months are all negative, which is to be expected in view of the inverse correlation between P and M. Multiple correlation coefficients were next computed between R_s and P, S and C; these are bigger than the largest simple correlation coefficient and range from 0·847 in February to 0·692 in May. This should be contrasted with the England and Wales case where the C index alone gives the main information about general raininess.

Association between the indices and temperature. Murray and Lewis[1] discussed the associations between central England* monthly mean temperatures and the indices, and subsequently Perry[5,6] showed the variations of the relationships over different parts of the United Kingdom from an analysis of district data for the period 1926 to 1966. In the present paper the discussion is based on correlations between the indices and monthly mean temperature at stations with long records over the United Kingdom, namely Plymouth, Kew, Oxford, Cambridge, Aberystwyth, Edgbaston, York, Scarborough, Durham, Armagh, Dumfries, Edinburgh, Aberdeen and Braemar, as well as at stations representative of central England.*

Table II lists the correlation coefficients applicable to central England.

TABLE II—CORRELATION COEFFICIENTS BETWEEN MONTHLY MEAN TEMPERATURE, T, IN CENTRAL ENGLAND AND P, S, C AND M INDICES, WITH MULTIPLE CORRELATION COEFFICIENTS BETWEEN T AND P, S AND C FOR THE PERIOD 1869–1968

T correlated with :	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
P	0·79	0·77	0·60	0·24	(0·03)	(−0·11)	(−0·12)	−0·24	(−0·03)	(0·10)	0·51	0·61
S	0·34	0·34	0·52	0·48	0·65	0·30	0·39	0·46	0·66	0·62	0·59	0·45
C	0·20	0·20	(−0·07)	−0·28	−0·22	−0·39	−0·55	−0·52	−0·27	(−0·01)	0·23	0·23
M	−0·33	(−0·16)	−0·28	−0·24	−0·28	−0·34	−0·22	(−0·05)	−0·28	(−0·13)	−0·23	(−0·09)
PSC	0·84	0·81	0·82	0·66	0·73	0·54	0·70	0·73	0·70	0·64	0·74	0·77

Correlation coefficients in brackets are not significant, correlations in bold are significant at the 1 per cent level, and the rest are significant at the 5 per cent level.

The main features of Table II are the positive correlations between S and T in all months, the positive correlations between P and T and between C and T in the colder part of the year and the negative correlations between C and T in the summer half-year. The best correlations in individual months are (i) between P and T in December, January, February and March, (ii) between S and T in April, May, September, October and November and (iii) between C and T in June, July and August. These results agree with the conclusions of Murray and Lewis.[1] The correlations (negative) between M and T are never greater (in absolute magnitude) than the correlations between T and any one of the indices P, S and C each month. In every month the multiple correlation coefficients, shown in the bottom line of Table II, are greater than any of the simple correlation coefficients. The highest multiple correlations occur in winter months and the lowest in June.

The regression equation for January mean temperature (T expressed in degrees Celsius) is

$$T = 2 \cdot 753 + 0 \cdot 058P + 0 \cdot 054S + 0 \cdot 006C. \qquad \dots (1)$$

In equation (1) P, S and C can be positive or negative within the range given in Appendix I. Clearly if P, S and C are all large positive values, as is the case when progressive, cyclonic and southerly types are dominant over the month, then high temperatures occur over central England. Very cold weather in January is of course associated with negative values of the indices, i.e. when blocked, northerly and anti-cyclonic types predominate. However, it is also evident that particular temperatures can be associated with quite

* Manley, G.; The mean temperature of central England 1698–1952. *Q. Jnl R. met. Soc.,* London, **79,** 1953, p. 242-261.

different types of monthly circulations in view of the range of possibilities for *P*, *S* and *C*.

The regression equation for August is

$$T = 15.816 - 0.009P + 0.077S - 0.035C . \qquad \ldots (2)$$

This equation confirms that the highest August temperatures are associated with blocked (negative *P*), southerly (positive *S*) and anticyclonic (negative *C*) weather types and the lowest temperatures with progressive, northerly, cyclonic weather types over the British Isles. In August the *C* and *S* indices are much more important than the *P* index, whereas the opposite is the case in January.

The *P*, *S*, *C* and *M* indices were correlated with monthly mean temperatures at other places scattered over the United Kingdom. At these stations, readily available temperature records covered 90 years or more. Correlation coefficients for a few stations are given in Table III; the data in this table, together with Table II, are sufficient to portray the main features of the spatial distribution of the correlations over the United Kingdom.

Examination of Table III in relation to Table II and data for other stations which are not reproduced, allows some generalizations to be made. Mean monthly temperatures over the United Kingdom are positively correlated with *P* from November to April, with the highest values in winter. Correlations are insignificant in May and October, but negative and rather weak from June to September over most districts except eastern parts of Britain. Temperature is, not surprisingly, positively correlated with *S* everywhere in all months, but the highest correlations are in May, September, October and November. Temperature is negatively correlated with *C* from April to September in all areas, with the largest negative correlations in high summer; clearly a mainly cyclonic month is generally cloudy and cool and an anticyclonic month is usually bright and warm in the summer half-year. In winter the situation is different. Cyclonic systems over the British Isles are obviously colder in the north than in the south. On the other hand, anticyclonic systems are much more likely to be colder in the southern and central areas than in the far north, owing to the greater coldness from continental winds and the greater likelihood of clear skies and radiational cooling. Thus it is not surprising that *T* and *C* are positively correlated over most of England and Wales and negatively correlated farther north from November to February, although the correlations are generally insignificant except in the south and in the far north. March and October are transitional months when weak negative correlations extend south over all areas except south-eastern England. Finally, temperature and *M* are mostly negatively correlated, as suggested by Braemar and central England data; the correlations are quite insignificant in August and December and usually small in other months.

The multiple correlation coefficients for Edinburgh are about the same size as for central England, the largest being 0.84 in January and the lowest 0.56 in June. The regression equation for January mean temperature at Edinburgh is

$$T = 2.479 + 0.050P + 0.049S - 0.034C . \qquad \ldots (3)$$

TABLE III—CORRELATION COEFFICIENTS BETWEEN MONTHLY MEAN TEMPERATURES, T, AT SPECIFIED PLACES AND CERTAIN P, S, C AND M INDICES

Place	T correlated with	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Braemar 1866–1966	P	0·70	0·64	0·49	0·24	(0·07)	(0·19)	(0·18)	−0·28	−0·22	(−0·05)	0·36	0·50
	S	0·37	0·25	0·34	0·34	0·48	(0·15)	0·25	0·37	0·62	0·57	0·53	0·45
	C	−0·23	−0·24	−0·37	−0·53	−0·35	−0·41	−0·53	−0·56	−0·40	−0·26	(−0·12)	−0·20
	M	−0·37	(−0·18)	−0·29	−0·21	−0·27	−0·25	(−0·10)	(0·02)	(−0·18)	(0·05)	(−0·13)	(−0·13)
Armagh 1871–1966	P	0·71	0·67	0·47	0·28	(−0·11)	−0·20	−0·20	−0·36	(−0·06)	(−0·03)	0·38	0·46
	S	0·37	0·39	0·49	0·34	0·52	(0·16)	0·32	0·32	0·65	0·60	0·57	0·49
	C	(−0·08)	(−0·07)	−0·29	−0·44	−0·39	−0·41	−0·52	−0·61	−0·35	−0·27	(−0·15)	(−0·10)
Scarborough 1872–1966	P	0·75	0·66	0·66	0·35	(0·18)	0·27	0·25	(−0·05)	(0·13)	(−0·04)	0·31	0·38
	S	0·30	0·23	0·36	0·25	0·52	(0·15)	0·42	0·39	0·57	0·56	0·51	0·41
	C	(0·09)	(0·00)	−0·24	−0·31	(−0·11)	−0·32	−0·28	−0·43	−0·23	(−0·15)	(−0·05)	(0·06)
Plymouth 1865–1966	P	0·75	0·73	0·50	(0·08)	(−0·11)	(−0·11)	(−0·23)	−0·35	(−0·08)	(−0·04)	0·46	0·55
	S	0·41	0·41	0·59	0·38	0·45	(0·06)	(0·15)	0·25	0·53	0·65	0·62	0·51
	C	0·26	0·32	(−0·06)	−0·31	−0·34	−0·56	−0·62	−0·64	−0·36	(−0·11)	0·20	0·34
Edinburgh 1869–1959	PSC	0·84	0·83	0·82	0·76	0·68	0·56	0·58	0·69	0·76	0·68	0·72	0·73

Correlation coefficients in brackets are not significant, correlations in bold are significant at the 1 per cent level, and the rest are significant at the 5 per cent level. Data were complete within the periods shown at Armagh and Edinburgh, but a few monthly mean temperatures were missing at the other stations.

This equation implies that progressive, southerly, anticyclonic months have the highest mean temperatures at Edinburgh in January, whereas blocked, northerly, cyclonic months are the coldest.

The regression equation for August temperature at Edinburgh is

$$T = 14.455 - 0.003P + 0.067S - 0.033C .\qquad\qquad \ldots (4)$$

From equation (4) it is inferred that the warmest Augusts are those with considerable blocking, southerly bias and anticyclonicity, whereas the coldest months are progressive, northerly and cyclonic.

The indices as indicators of anomalous circulation. The *PSCM* indices are very useful as parameters for specifying large-scale anomalous circulations, such as might be indicated by monthly or seasonal pressure anomaly maps. Examples of mean pressure anomaly maps for one-, two- and three- monthly periods are shown in Figures 2, 3 and 4 respectively.
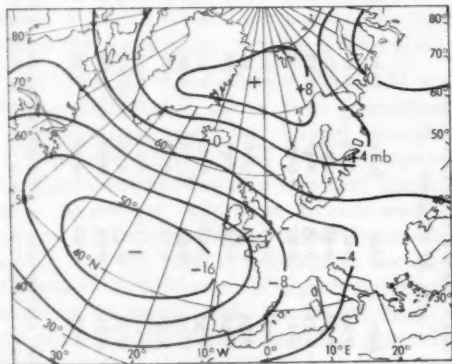

FIGURE 2—MONTHLY MEAN PRESSURE ANOMALIES FOR JANUARY 1970
Anomalies are departures from monthly averages for the period 1873–1968.

January 1970 is classified as $P_1 S_5 C_5 M_5$ or very blocked, southerly, cyclonic and meridional. P_1 and S_5 together indicate an anomalous bias to south-easterly. The fact that both S and M are in quintile 5 suggests that southerly types predominated and that some northerly types also occurred, or that the southerly types were extremely frequent. The mean pressure anomaly map, Figure 2, is quite consistent with the *PSCM* indications. The very wet period from September to October 1967 is classified as $P_5 S_4 C_5 M_1$ or progressive, southerly and cyclonic but less meridional than usual. P and S together imply much more west to south-west flow than usual, but little or no northerly in view of M_1. Much more cyclonic weather than usual is indicated by C_5; and from this index in conjunction with P_5 it is inferred that very unsettled weather predominated with depressions often moving east or north-east over or near the north of Britain. The anomaly pattern shown in Figure 3 clearly gives much the same picture as the $P_5 S_4 C_5 M_1$ classification. The seasonal example shown in Figure 4 refers to the fine summer of 1947. The positive anomaly centre over south Norway and the pronounced south-easterly anomalous flow over Britain agree well with the

index classification of P_1 S_5 C_1 M_1 . In general it has been found that the main features of the large-scale circulation as shown by pressure anomaly patterns near the British Isles are well represented by the *PSCM* indices in quintile classes except when the circulation is not very abnormal.
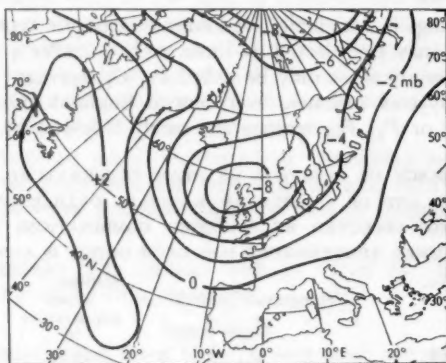

FIGURE 3—MEAN PRESSURE ANOMALIES FOR SEPTEMBER/OCTOBER 1967
Anomalies are departures from two-monthly averages for the period 1873–1968.
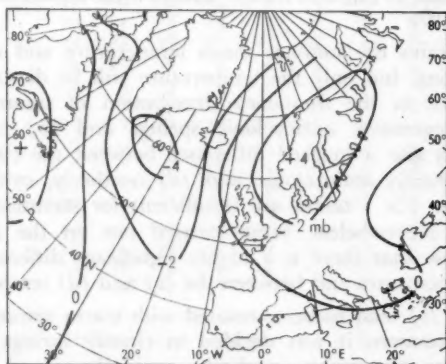
FIGURE 4—SEASONAL MEAN PRESSURE ANOMALIES FOR SUMMER 1947
Anomalies are departures from seasonal averages for the period 1873–1968.

Applications of the indices in long-range forecasting. The indices have been employed in recent years in helping to select monthly analogues. They may also be used in seasonal forecasting. The indices are particularly useful in this respect when the large-scale circulation over the Atlantic and Europe is very anomalous. Classes of years with broad-scale similarity in circulation over periods of from one to three months can readily be selected with the help of the indices. In practice it is not generally possible to obtain an adequate statistical sample of analogues if close similarity in each index is insisted upon. However, useful results have been obtained by selecting analogues from pairs of the indices when they suggest broadly similar anomalous

circulations. The weather in the sequel period can readily be obtained and in many cases rainfall and/or temperature tend to have dominant character-istics. One or two cases have already been described by Murray.[7,8] It is not proposed to give a comprehensive account here, but another illustration may be appropriate.

Years with springs in which the predominant synoptic types are progressive and anticyclonic may be selected as those with quintiles 4 or 5 in P and 1 or 2 in C. For brevity these may be called $P_{45} C_{12}$ springs. Such springs are rarely followed by cool summers over central England. On the other hand blocked, cyclonic or $P_{12} C_{45}$ springs are rarely followed by warm summers.

TABLE IV—FREQUENCY OF QUINTILES OF MEAN TEMPERATURE IN SUMMER OVER CENTRAL ENGLAND AND OF TERCILES OF RAINFALL OVER ENGLAND AND WALES FOLLOWING SPRINGS SELECTED BY SPECIFIED COMBINATIONS OF P, S AND C INDICES. MEAN SUMMER TEMPERATURE FOR EACH GROUP IS ALSO GIVEN

	Spring type	No.	Temperature quintile					SUMMER Mean temperature °C	Rainfall tercile		
			1	2	3	4	5		1	2	3
(a)	$P_{45}C_{12}$	18	0	3	5	5	5	15·64	8	7	3
(b)	$P_{12}C_{45}$	13	4	4	4	1	0	14.68	3	3	7
(c)	$S_{45}C_{12}$	18	0	3	4	5	6	15·71	7	8	3
(d)	$S_{12}C_{45}$	15	5	2	4	3	1	14·91	5	2	8

Temperature quintile boundaries (1 is very cold) are based on data for the period 1874–1963 with no allowance made for long-term change. Rainfall tercile boundaries (1 is dry) are based on the period 1866–1965.

Table IV contains the summer mean temperature and rainfall following four types of spring, but only the temperature will be discussed. There is a marked difference in the frequency distribution of summer temperatures between *(a)* progressive, anticyclonic springs and *(b)* blocked, cyclonic springs. There is also a marked difference between the contrasting springs of type *(c)* southerly, anticyclonic and *(d)* northerly, cyclonic. However, the data in these 5 × 1 tables are insufficient for statistical testing by the chi-square test. Nevertheless, *t*-tests carried out on the average summer temperatures show that there is a highly significant difference between the *(a)* and *(b)* temperatures and between the *(c)* and *(d)* temperatures.

Since *(a)* and *(c)* tend to be associated with warm summers and *(b)* and *(d)* with cool summers, it was decided to classify springs into two types: (i) $P_{45} S_{45} C_{12}$ or progressive, southerly, anticyclonic and (ii) $P_{12} S_{12} C_{45}$ or blocked, northerly, cyclonic. These criteria drastically reduced the number of cases. There are only five springs of type (i), namely 1868, 1914, 1933, 1943 and 1945; four of the summers of these years were warm *(T_4 or T_5)* and one was average *(T_3)*. Only three type (ii) springs are in the record, namely 1888, 1891 and 1951; the first two were cool *(T_1 and T_2 respectively)* and 1951 was on the boundary between T_2 and T_3. Incidentally, none of the type (i) summers was wet and none of the type (ii) summers was dry.

More stringent criteria for selecting springs could be adopted, for instance by insisting on only extreme quintiles in the indices, but then the number of cases is reduced even further.

Concluding remarks. These revised and extended data confirm and refine the synoptic climatology which was presented in earlier papers.[1,5,6]

The *PSCM* indices are of course only one way of looking at the broad-scale circulation. Recently Hay[9] has employed monthly mean pressure maps for classifying synoptic types near the British Isles, and his results have a good deal in common with the work on *PSCM* indices. However, the indices have some advantages such as the ease of computation for any period, for example for 30 days from mid-month or for 90 days, etc. Moreover, they appear to reflect well the main features of the daily synoptic types and the percentile form of the indices is particularly suitable for relating them to anomalous features of the broad-scale circulation which are better represented by mean pressure anomaly maps than by mean pressure maps.

The *PSCM* indices are useful in long-range forecasting but of course they should generally be considered with other procedures, such as the approach through sea temperature anomaly patterns recently suggested by Ratcliffe and Murray.[4]

Appendix I

Quintile boundary values of *P, S, C* and *M* for *(a)* each month and *(b)* each season, based on the 100 years from 1869 to 1968.

(a) Month

Index	Boundary	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
P	5-4	35	31	20	11	5	15	34	34	24	25	23	36
	4-3	17	8	9	-4	-4	5	17	22	13	8	11	24
	3-2	10	-4	-8	-13	-19	-6	8	8	-2	-4	3	13
	2-1	-2	-23	-28	-21	-28	-16	-4	-8	-13	-22	-14	0
S	5-4	12	11	9	5	5	3	2	4	7	9	8	10
	4-3	7	5	3	1	0	-2	-2	0	3	4	3	4
	3-2	0	0	-5	-5	-5	-5	-6	-3	-1	-2	-4	-1
	2-1	-7	-9	-11	-10	-11	-11	-10	-7	-6	-5	-9	-6
C	5-4	6	9	10	6	6	5	12	15	3	9	10	7
	4-3	0	-1	-1	-2	-2	-2	5	6	-3	0	1	2
	3-2	-7	-10	-11	-9	-9	-8	-4	-3	-9	-8	-5	-5
	2-1	-16	-17	-17	-15	-16	-17	-14	-13	-20	-17	-16	-13
M	5-4	21	19	21	21	22	18	20	16	18	20	20	19
	4-3	16	15	18	17	18	14	15	13	14	15	16	15
	3-2	12	12	14	14	15	11	11	10	12	12	12	20
	2-1	9	7	10	11	11	9	8	7	8	8	8	9

(b) Season

Index	Boundary	Winter	Spring	Summer	Autumn
P	5-4	69	5	57	51
	4-3	45	-16	33	26
	3-2	32	-32	23	0
	2-1	-7	-49	-7	-24
S	5-4	18	5	3	11
	4-3	11	-4	-7	3
	3-2	3	-12	-14	-4
	2-1	-9	-19	-23	-16
C	5-4	12	4	15	6
	4-3	-8	-7	1	-10
	3-2	-20	-23	-10	-22
	2-1	-34	-39	-27	-36
M	5-4	52	57	46	50
	4-3	44	50	40	44
	3-2	39	43	36	39
	2-1	33	37	30	32

Note: Quintile 5 applies when index value is ≥ boundary 5-4, quintile 4 when it is ≥ boundary 4-3 and < boundary 5-4, etc.

Appendix II

Extreme values of *P, S, C* and *M*, with dates of occurrence, during the period 1861–1969 for
(a) each month, *(b)* each season and *(c)* the whole year.

(a) Month

	P		S		C		M	
Jan.	62	(1921)	26	(1924)	27	(1948)	40	(1967)
	−52	(1941, 1963)	−23	(1945)	−36	(1880)	0	(1921)
Feb.	58	(1868)	24	(1872)	24	(1925)	27	(1924)
	−55	(1932)	−24	(1965)	−37	(1934)	4	(1954)
Mar.	60	(1861)	24	(1957)	34	(1909)	30	(1869)
	−48	(1931)	−28	(1869)	−46	(1929)	1	(1934)
Apr.	48	(1943)	14	(1902)	21	(1920)	27	(1928)
	−49	(1861)	−21	(1919)	−45	(1893)	0	(1948)
May	26	(1956)	19	(1867)	28	(1889)	33	(1954)
	−52	(1869)	−29	(1902)	−45	(1896)	2	(1911)
June	42	(1864, 1890)	15	(1935)	29	(1912)	32	(1909)
	−46	(1958)	−32	(1909)	−36	(1889)	1	(1875)
July	53	(1881)	18	(1884)	30	(1936)	34	(1919)
	−41	(1867)	−34	(1919)	−42	(1955)	1	(1920)
Aug.	62	(1861)	17	(1884)	38	(1912)	31	(1887)
	−44	(1947)	−25	(1896)	−38	(1955)	1	(1874)
Sept.	57	(1923, 1950, 1954)	17	(1901)	29	(1866)	28	(1877, 1952)
	−49	(1894)	−28	(1952)	−43	(1959)	3	(1879, 1917, 1966)
Oct.	56	(1967)	30	(1908)	38	(1907)	30	(1908, 1919)
	−53	(1960)	−23	(1887)	−33	(1962)	2	(1942)
Nov.	57	(1877)	25	(1881)	29	(1963)	30	(1878)
	−46	(1945)	−30	(1878)	−35	(1867)	2	(1883, 1887, 1907)
Dec.	59	(1898)	25	(1934)	29	(1876)	32	(1878)
	−49	(1927)	−26	(1878)	−32	(1931)	2	(1930)

(b) Season

	P		S		C		M	
Winter	107	(1869)	44	(1913)	42	(1877)	71	(1924)
	−94	(1963)	−46	(1965)	−82	(1932)	16	(1919)
Spring	70	(1921)	29	(1942)	36	(1889)	75	(1928)
	−91	(1928)	−43	(1962)	−88	(1893)	19	(1920)
Summer	112	(1923)	19	(1884)	70	(1912)	63	(1919)
	−52	(1885)	−59	(1919)	−87	(1869)	13	(1905)
Autumn	131	(1917)	53	(1920)	35	(1935)	72	(1876)
	−81	(1915)	−53	(1952)	−64	(1945)	16	(1954)

(c) Year

	P		S		C		M	
	263	(1923)	64	(1924)	124	(1872)	229	(1878)
	−105	(1963)	−106	(1919)	−160	(1893)	119	(1905, 1920)

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A GEOMETRICAL INTERPRETATION OF THE KINEMATICS OF TWO-DIMENSIONAL FLOW

By R. DIXON and T. H. KIRK

Although vorticity and divergence are familiar terms in elementary meteorology, the role of the deformation is perhaps a little more obscure, although its importance has been stressed, for example by Petterssen.[1] This note attempts a clarification, based on a simple geometrical interpretation.

If we consider two-dimensional flow, having velocity components (u, v), then the vorticity (ζ), the divergence (D) and 'components' of deformation (α, β) may be defined as follows :

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} , \quad D = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} ,$$

$$\alpha = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} , \quad \beta = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} ,$$

where the deformation F is given by $F^2 = \alpha^2 + \beta^2$. The quantities ζ and D are independent of the system of axes chosen, and so is F, but the components α and β vary with the choice of axes.

It is convenient now to visualize two-dimensional flow in terms of speed (V), given by the distribution of isotachs, and direction (ψ), given by the distribution of isogons. Taking a right-handed system of unit vectors $(\mathbf{t}, \mathbf{n}, \mathbf{k})$, where $\mathbf{t}$ denotes direction along the flow, $\mathbf{n}$ perpendicular to the flow and $\mathbf{k}$ vertical, new vectors $\mathbf{P}$ and $\mathbf{R}$ may be defined as follows :

$$\mathbf{P} = A\mathbf{t} + B\mathbf{n},$$
$$\mathbf{R} = D\mathbf{t} - \zeta\mathbf{n},$$

where $A = \dfrac{\partial V}{\partial s} - V\dfrac{\partial \psi}{\partial n}$ and $B = \dfrac{\partial V}{\partial n} + V\dfrac{\partial \psi}{\partial s}$;

$\partial/\partial s$ represents differentiation along the streamlines and $\partial/\partial n$ represents differentiation along the orthogonals; A and B are the 'components' of deformation in this intrinsic system, and so $F^2 = A^2 + B^2$.

It can be shown that the plane vectors

$$\mathbf{P} = A\mathbf{t} + B\mathbf{n} = \nabla V + \mathbf{k} \times V\nabla\psi \qquad \ldots (1)$$

$$\text{and } \mathbf{R} = D\mathbf{t} - \zeta\mathbf{n} = \nabla V - \mathbf{k} \times V\nabla\psi \qquad \ldots (2)$$

where ∇, operating on a quantity, denotes its gradient.

Equations (1) and (2) give **P** and **R** in terms of the isotachs and isogons of the flow field. For any flow for which speed (V) and direction (ψ) are known at each point, it is possible to construct a diagram (Figure 1) as follows :

    (i)   Draw **t** and **n** axes at right angles.

   (ii)   In the (**t**, **n**) plane, draw OX to represent ∇V in magnitude and direction and OY to represent $\mathbf{k} \times V\nabla\psi$ in magnitude and direction.

  (iii)   Complete the parallelogram OYZX.

Then, from equation (1), **P** is represented by OZ, the projections of OZ on the **t** and **n** axes represent A and B respectively, and the magnitude of OZ represents F.

Similarly, from equation (2), **R** is represented by YX, the projections of YX on the **t** and **n** axes represent D and ζ respectively, and the magnitude of YX represents $\sqrt{(\zeta^2 + D^2)}$.

One thus obtains a diagrammatic characterization of plane flow fields. If, for example, the flow is solenoidal, i.e. $D = 0$, then the diagram must be such that **R** is parallel to **n**. Alternatively, for irrotational flow, $\zeta = 0$ and the vector **R** must be parallel to **t**.

If OX and OY are equal in magnitude, then the figure OYZX becomes a rhombus. Since the diagonals of a rhombus intersect at right angles, it follows that in this particular case **P** and **R** are orthogonal vectors. This implies that

$$AD - B\zeta = 0, \qquad \text{i.e.} \quad \frac{A}{\zeta} = \frac{B}{D}.$$
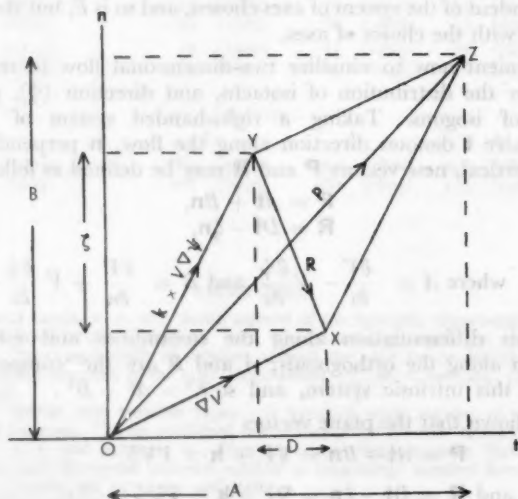
FIGURE I—DIAGRAMMATIC CHARACTERIZATION OF PLANE FLOW FIELDS

If OX and OY are at right angles and the rectangle OYZX is oriented so that **R** is approximately parallel to **n** then the diagram is characteristic of geostrophic motion. This follows since Div $\mathbf{V} \approx 0$, and by virtue of the fact that OX and OY are at right angles, $-\nabla V \cdot \mathbf{k} \times V\nabla \psi = 0$.

But $-\nabla V \cdot \mathbf{k} \times V\nabla \psi \equiv J(u, v)$, and thus $J(u, v) = 0$, which is also approximately true for geostrophic motion.

Now consider the application of the cosine rule to triangle OXY. We have

$$R^2 = OX^2 + OY^2 - 2OX \cdot OY \cos XOY . \qquad \ldots (3)$$

From (1) and (2)

$$OX = |\nabla V| = \tfrac{1}{2}|(A + D)\mathbf{t} + (B - \zeta)\mathbf{n}|$$
$$OY = |\mathbf{k} \times V\nabla\psi| = \tfrac{1}{2}|(A - D)\mathbf{t} + (B + \zeta)\mathbf{n}|$$
and $$OX.OY \cos XOY = \nabla V \cdot \mathbf{k} \times V\nabla\psi = -J(u, v).$$

Substitution in (3) leads to
$$F^2 = A^2 + B^2 = \zeta^2 + D^2 + 4\nabla V \cdot \mathbf{k} \times V\nabla \psi.$$

Hence
$$F^2 = \zeta^2 + D^2 - 4J(u, v) ,$$

which is the two-dimensional form of Hamel's Identity.[2]

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REVIEWS

Picture atlas of the Arctic by R. Thorén. 295 mm × 215 mm, pp. xii + 449, *illus.* Elsevier Publishing Co., 22 Rippleside Commercial Estate, Barking, Essex, 1969. Price: £19.

This is a substantial reference manual on the Arctic. Many aspects are touched on and illustrated — geography, navigation, transport, climate and ocean currents, radio communication, geology, natural resources and so on. The author, a retired captain of the Swedish Navy and now a consultant in photographic interpretation at the Research Institute of National Defence, Stockholm, is an expert in photogrammetry and photographic intelligence, his knowledge and experience acquired not only in Sweden but in several other European countries as well as the U.S.A. and Canada. Acknowledgement of help and encouragement in production of the book is made to the author's friends and colleagues in many countries, including one or two Soviet scientists. The book is, however, chiefly a picture book, a collection of nearly 600 photographs remarkable for their clarity (within the limits of magnification allowed by the screen used in the printing blocks). There are only some 14 maps which, however, include a detailed bathymetric chart (p. 2) of the Arctic Ocean (compressed into half a page and on an unnecessarily small scale) incorporating the latest knowledge. This brings out the two deep

basins in the Arctic, the depth of the channel between Spitsbergen and Green-land, and the extraordinary breadth of the continental shelf north of Siberia. Most of the latter was dry land in the ice age, and in the early postglacial millennia of warmest climate forest spread to near 75°N (p. 404) as against the northernmost limit at 72·4°N 105°E today.

The book will be of prime use to the geographer and to intending Arctic travellers. Many of the (often very beautiful) photographs, taken from the ground and from the air, a number of them being stereopairs taken looking vertically downward, contribute a magnificent album of illustrations of geomorphological (especially ice-age) processes and ice forms, an incomparable reference for teachers and students of these subjects. Some may regard it as indispensable.

The coverage of different areas and different topics is rather uneven, as illustrated by the following table :

Area	Pages of text	Pages of pictures	Number of pictures
Arctic Ocean	14	37	61
Drifting ice stations	9	13	29
Alaska, north of the Arctic circle	4	13	20
Canadian Arctic	77	77	88
Greenland	5	30	63
Iceland	3	2	6
Norwegian islands in the Arctic	7	70	120
Arctic Scandinavia	13	83	146
Soviet Arctic	15	21	45

The frontispiece, a circumpolar map of the Arctic engraved in 1578 by Gerardus Mercator, is of unusual interest. Its central feature, a polar continent within about the 77th parallel of latitude, is pure fantasy; the rivers and Arctic coast of Siberia are wildly erroneous; but much of the rest is oddly near the truth, including the over-all relationships and the position and shape of Bering Strait as well as of a somewhat diminutive Hudson Bay. One cannot help wondering how much various Viking explorers had seen and how much knowledge of it survived in various places until Mercator's time. This and the photograph (Figure 573) of the mammoth recovered from the fossile ice amongst the still frozen ground of north-east Siberia, as well as all the miscellaneous information about the high-atmosphere rocket-sounding range at 81°N in Franz Josef Land, the thickness of the permafrost layer (up to 400 metres) in various places, the use of helicopters, hovercraft, hydro-foils and aerosledges, and many other items, from the first Arctic flight by balloon in 1897 by the Swedish scientist Andrée (p. 219) to the future role of submarine tankers and traders, are prizes of the author's skill as a collector.

Nevertheless the text has weaknesses, despite the high price. Perhaps the project demanded too wide a range of knowledge and judgement. In far too

many of the photographs it is difficult (or impossible) to gain any idea of scale. The illustration of the development of ice forecast maps for shipping on the Arctic coasts by a manifest forecast failure (p. 77 and Figures 110–112) is a strange choice if, perhaps, a worth-while warning. The physical phenomena (pingoes, ice wedges, polygon patterned ground, etc.) illustrated are inadequately, if at all, explained. The climate figures quoted are few and haphazard, a mean January temperature here, an extreme there, a July temperature in another place. The sizes of some glaciers in Sweden are given, but not of others, including the largest. Many references to climatic prehistory and to climatic changes in progress today are unreliable. The text implies (p. 301) that there was just one long ice age, lasting throughout the Pleistocene, in Finland and (on p. 225) that there could even have been in the ice age some massive ice-cap covering the Arctic Ocean basin. The Arctic warming of the earlier part of this century is repeatedly described in Ahlmann's language of the 1940s as 'the present climate fluctuation': against this background, the historic closing of Russia's open winter port of Murmansk by ice in 1965–66 is unexplained. The event is misleadingly ascribed to a freak cold winter in northernmost Scandinavia, and the appearance of the Arctic sea ice in a belt along the coast is not mentioned.

A nasty taste is unfortunately introduced by the few paragraphs on submarine warfare in the Arctic without conveying much information likely to be of use either to the strategists or to those who would oppose the whole suggestion tooth and nail. More interesting, and given in rather more detail, are the accounts of the development of the Soviet and Scandinavian rail and road networks which converge towards Lapland and the ice-free Atlantic ports.

There are inaccuracies and incautious statements in other realms, ranging from celebration of the fiftieth anniversary of 'Soviet polar aviation' in 1964 to the description of Beerenberg on Jan Mayen as an 'extinct volcano' (the last eruption was in 1818), and from the First International Geophysical (for this read *Polar*) Year in 1882–83 to tracked vehicles moving over 'bottomless marshes'.

It can be agreed (p. 221) that 'glaciers are very sensitive registers of climatic fluctuations', and the great twentieth century glacier recession from the advanced positions of 1650–1850 is richly documented in this book by pictures from Greenland and Spitsbergen as well as from Scandinavia. But their response to changes of climatic tendency is by no means as quick as that of the polar sea ice: hence the misunderstanding about Murmansk in 1965–66 and the omission of reference to present alarms in Iceland. One learns with interest of the increasing volume of shipping on the Soviet-operated Northern Sea Route (the famous North East Passage) and of convoys to readmit foreign shipping after 1967, against an ever-increasing provision of icebreakers — up to 10 icebreakers in action on one section of the route in 1965 and 1966.

In spite of all these reservations, the book is a mine of information, most of it broadly trustworthy, and a wonderful treasury of photographs.

                                                                            H. H. LAMB

Rainstorms and hail, by G. K. Sulakvelidze. 250 mm × 180 mm, pp. xx + 320,
  illus. (translated from the Russian by the Israel Program for Scientific
  Translations, Jerusalem), H. A. Humphreys Ltd, 5 Great Russell Street,
  London WC1, 1969. Price: 108s.

This book is effectively a second edition of *Formation of precipitation and
modification of hail processes* by Sulakvelidze, Bibilashvili and Lapcheva which
appeared in English in 1967 and was reviewed by K. A. Browning in the
Meteorological Magazine for February of last year.

The earlier book described the theories of hail formation developed at
the High-Mountain Geophysical Institute (VGI) in the U.S.S.R. and some
early experiments in hail suppression using techniques developed on the
basis of these theories. The opening chapters of *Rainstorms and hail* contain
essentially the same theoretical treatment as the previous publication,
together with some relatively minor additions to take account of more recent
developments. The closing chapters of the book — which are probably the
most significant part — describe the extension of the hail suppression technique
in the years 1964, 1965 and 1966 to protect larger areas in the Northern
Caucasus and in Transcaucasia — two regions which have significantly
different climatic conditions for hail formation.

The results of these experiments are very impressive indeed. Thus in 1964
an area of 292 000 hectares of agricultural crops was brought under protection
and only 5·3 per cent of this area was damaged by hail, compared with 9 per
cent of a corresponding control area. The corresponding figures for 1965
were 303 000 hectares protected, 3·5 per cent damaged compared to 19 per
cent in the control area and for 1966, 546 000 hectares protected, 1·1 per cent
damaged compared with 6·9 per cent in the control area. Thus, although
the area under protection was increased each year, the damage to the
protected area apparently continued to be markedly less than in the corres-
ponding control area. Sulakvelidze also evaluates several different effectiveness
criteria which take into account the natural variation from year to year in
the ratio of hail damage on the protected and control areas, and these indicate
that there is a definite positive effect for each year, with the possible exception
of 1964.

There are however several aspects of the work which lead one to share the
opinion which Dr Browning expressed in his review that the results are 'almost
too good to be true'. Firstly, the new book does little to dispel the doubts
which the earlier one raised about the theoretical model of a hailstorm on
which the experiments are based. In particular, it is still supposed that there
is an 'accumulation zone' in which large numbers of supercooled raindrops
collect to give very large liquid water contents at temperatures below 0°C,
but there is little evidence that theoretical models have taken into account
the three-dimensional nature of the airflow in convective storms.

Secondly, Sulakvelidze states (p. 258) that the boundaries of the hail growth
zone need to be located to within 100 metres and that the size of the hail
particles must be estimated. He claims that this is done by using 3- and
10-cm radars, although, as Dr Browning pointed out, there are very con-
siderable difficulties in understanding how this can be done when one
considers the variable attenuation of the 3-cm radar beam by the heavy
precipitation produced by a hailstorm.

Sulakvelidze also states that it is necessary to introduce into the hail-focus a reagent (either silver iodide or lead iodide) which will cause a proportion of the large, supercooled raindrops to freeze. This is done by firing 'El'brus – II' missiles from the ground into the hail-focus where they explode and disperse the crystallizing reagent. Again it is surprising that the required accuracy can be achieved when one considers the vigorous up- and down-draughts which exist in hailstorms. The explanation may, of course, be that the identification of the hail-focus is not as critical as Sulakvelidze suggests. In any case, it certainly seems very sensible to disperse the nucleating agent as near to the centre of the storm as possible and it would appear that the Russian workers have developed a technique which achieves this objective.

Finally, however, the impression of 'too good to be true' is most strongly conveyed by Sulakvelidze's explanation of the occasions on which hail damage occurred within the protected area purely in terms of failures in the logistics of the field operation. Thus he states (p. 281) that in 1966 when a total area of 1 million hectares was under protection, there were only 22 cases of (mainly weak) hail damage and that these could be accounted for as follows: 7 cases were a result of the work being stopped owing to civil flights, 10 cases were due to the equipment being out of order and the remaining 5 cases were due to 'incorrect application of the hail modification method'.

Despite these misgivings, the results reported in this book are undoubtedly of the greatest significance for all who are interested in the problem of hail prevention. We can only await with interest the results of further work in the U.S.S.R. following the decision made by the Soviet government in April 1967 to extend the protection scheme to every area in the Soviet Union damaged by hail and also the results of attempts to apply the same techniques to hailstorms in Canada and the U.S.A.

J. T. BARTLETT

Planetary electrodynamics, Volume 2, edited by S. C. Coroniti and J. Hughes. 230 mm × 150 mm, pp. xx + 503, *illus.*, Gordon and Breach Science Publishers, 12 Bloomsbury Way, London WC1, 1970. Price: £10.

This is the second of two volumes containing papers presented at the Fourth International Conference on the Universal Aspects of Atmospheric Electricity, held in Tokyo in 1968 (the date and place are not mentioned explicitly). This volume contains the proceedings of sessions five to eight of the conference, including edited discussions on the papers. The volume includes 10 papers on the monitoring of global thunderstorm activity (with particular interest in satellite observations and lightning flash counters) and 8 on the simulation of atmospheric electrical phenomena. Two sections (over half the book) are on the electrical properties of the stratosphere, ionosphere and interplanetary space, and the methods of measuring these properties. A novel suggestion emerges from a development of electrohydrodynamic phenomena by Carstoiu (p. 277) that thunderclouds might represent clusters of magnetically polar particles!

This book with its companion volume should be of interest to research workers in this field.
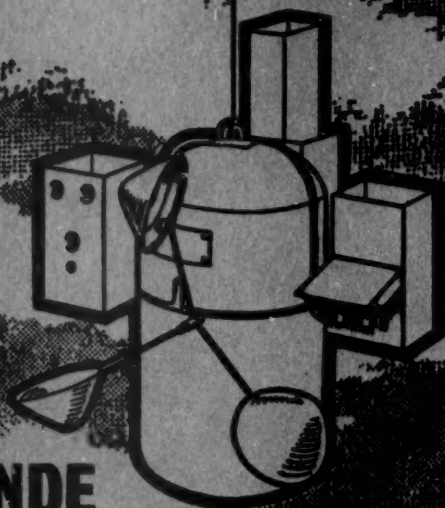
D. A. JOHNSON

HONOUR

The following award to a member of the staff of the Meteorological Office
has been announced:

I.S.M.

Mr. Bernard A. Blowers, Radio Supervisor at Headquarters Meteorological
Office, Bracknell.

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